We perform a seismic study of the young massive β Cephei star HD 203664 with the goal to constrain its interior structure. Our study is based on a time series of 328 new Geneva 7-colour photometric data of the star spread over 496.8 days. The data confirm the frequency of the dominant mode of the star which we refine to $f_1 = 6.02885\,\mathrm{c\,d^{-1}}$. The mode has a large amplitude of 37 mmag in V and is unambiguously identified as a dipole mode ($\ell = 2$) from its amplitude ratios and non-adiabatic computations. Besides f_1, we discover two additional new frequencies in the star with amplitudes above 4σ: $f_2 = 6.82902\,\mathrm{c\,d^{-1}}$ and $f_3 = 4.81543\,\mathrm{c\,d^{-1}}$ or one of their daily aliases. The amplitudes of these two modes are only between 3 and 4 mmag which explains why they were not detected before. Their amplitude ratios are too uncertain for mode identification. We show that the observed oscillation spectrum of HD 203664 is compatible with standard stellar models but that we have insufficient information for asteroseismic inferences. Among the large-amplitude β Cephei stars, HD 203664 stands out as the only one rotating at a significant fraction of its critical rotation velocity ($\sim 40\%$).

Key words. Stars: oscillations; Stars: variables: early-type – Stars: individual: HD 203664

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Multiperiodicity in the large-amplitude rapidly-rotating β Cephei star HD 203664*

C. Aerts[1,2], P. De Cat[3], J. De Ridder[1,**], H. Van Winckel[1], G. Raskin[1,4], G. Davignon[1,4], K. Uytterhoeven[1,4,***]

[1] Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200 B, B-3001 Leuven, Belgium
[2] Department of Astrophysics, Radboud University Nijmegen, PO Box 9010, 6500 GL Nijmegen, the Netherlands
[3] Koninklijke Sterrenwacht, Ringlaan 3, 1180 Brussel, Belgium
[4] Mercator Telescope, Calle Alvarez de Abreu 70, 38700 Santa Cruz de La Palma, Spain

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Abstract.

1. Introduction

The β Cephei stars are a homogeneous group of oscillating B0–B3 stars that have been studied as a class for more than a century now. Stankov & Handler (2005) recently compiled an overview of the observational properties of this group of stars. The oscillations of β Cephei stars are explained in terms of the κ mechanism operating in the ionisation layer of the iron-peak elements (Cox et al. 1992; Kiriakidis et al. 1992; Moskalik & Dziembowski 1992; Dziembowksi & Pamyathnykh 1993). Given that mainly low-degree low-order pressure and gravity modes are excited, these stars are good potential targets for in-depth seismic studies of the interior structure of massive (i.e. pre-supernova) stars. Indeed, the luminosity classes of the known β Cephei stars range from V up to I (Stankov & Handler 2005; see also Waelkens et al. 1998) and theory predicts the occurrence of oscillations for this whole area in the HR diagram (Pamyatnykh 1999).

Recent progress in the seismic interpretation of selected β Cephei stars was remarkable in the sense that standard stellar structure models are unable to explain the oscillation data for the best-studied stars: HD 129929 (Aerts et al. 2003), ν Eridani (Pamyatnykh et al. 2004, Ausseloos et al. 2004), 12 Lacertae (Handler et al. 2005, Ausseloos 2005). Pamyatnykh et al. (2004) have suggested to include radiative diffusion processes in a new generation of stellar models in an attempt to resolve the excitation problem in ν Eridani. This has not yet been achieved so far. These three well-studied β Cephei stars are all slow rotators with vsini below 40 km s^{-1} and a mass between 9 and 12 M$_\odot$.

In view of these recent achievements, and in an attempt to obtain similar results for a star with higher surface rotation velocity, we have selected one of the most rapid rotators among the large-amplitude β Cephei stars for a long-term photometric monitoring programme on which we report here.

The star HD 203664 (B0.5V, m$_{\rm V}$=8.59) was discovered to be a new β Cephei star by Aerts (2000), who derived one frequency of 6.0289 c d^{-1} from the HIPPARCOS photometry. This frequency was confirmed by her in 49 Geneva measurements spread over about one year taken with the P7 photometer attached to the 0.7m Swiss telescope at La Silla observatory. The scarce multicolour data set did not allow discrimination between $\ell = 1$ or 2 for the spherical degree of this oscillation mode but did seem to exclude a radial mode. HD 203664 is among the top ten of the class as far as photometric amplitude is concerned, with a value of $\sim$30mmag in the Geneva V filter (Aerts 2000). It is by far the most rapid rotator among the large-amplitude members (see Fig. 4 of Stankov & Handler 2005), with vsini=200 km s^{-1} derived from high-resolution spectra by Little et al. (1994). HD 203664 also happens to be one of the very few class members which is situated at high galactic latitute ($l = 61.^\circ 93, b = -27.^\circ 46$) at a distance of 3200 pc, thanks to which high-precision spectroscopic data is available and carefully analysed (Little et al. 1994).

In this paper, we report the findings of our observational study of HD 203664 in an attempt to contribute to a better understanding of β Cephei stellar structure models in a diversity of such type of stars.

2. Data description and stellar parameters

We included HD 203664 in the long-term photometric monitoring programme of pulsating stars performed with the 1.2m Mercator telescope at Roque de los Muchachos in La Palma,

* Based on data gathered with the 1.2m Mercator telescope equipped with the photometer P7 situated at Roque de los Muchachos, La Palma
** Postdoctoral Fellow of the Fund for Scientific Research of Flanders (FWO)
*** Present address: Center for Astrophysics, University of Central Lancashire, Preston PR1 2HE, UK

Canary Islands. In this framework we obtained 328 Geneva 7-colour high-precision photometric measurements between HJD 2452085.6 and HJD 2452582.3. The time span of these new data is 496.8 days. The integration times were typically 4 minutes, resulting in a precision of about 7 mmag per measurement in U and 6 mmag in V. Aerts (2000) had obtained already 49 datapoints for the star between HJD 2450391 and HJD 2450790 with the same instrument but attached to the 0.7m Swiss telescope at La Silla. The Southern and Northern Geneva standard star systems are carefully calibrated so that measurements in both hemispheres should be compatible, even over a long baseline. All reduced data are provided in Table 1.[1]

The basic stellar parameters of HD 203664 were derived from different sources. Aerts (2000) used the old Geneva photometry and positioned the star in the HR diagram with respect to the β Cephei star instability strip (see her Fig. 1). Using standard stellar models published by Schaller et al. (1992), she thus derived a mass of $13.8 M_\odot$. We have recomputed the estimates using the same method as in Aerts (2000) from the average value of the 6 Geneva colours for all new data and find refined values of $\log T_{\rm eff} = 4.47 \pm 0.01$, $\log g = 3.9 \pm 0.3$.

It is well-known, however, that fundamental parameter estimates for B stars from high-resolution spectroscopy often result in a lower effective temperature and gravity (see, e.g. De Ridder et al. 2004 for a discussion about this for the β Cephei star ν Eridani). Moreover, in the case of HD 203664 we cannot rely on an accurate value of the parallax, as shown by the large discrepancy between the result of 0.32 mas by Little et al. (1994) and of 2.23 ± 1.08 mas from HIPPARCOS (Perryman et al. 1997). Little et al. (1994) derived the stellar parameters from high-resolution spectra and used these to estimate the distance. They find $\log T_{\rm eff} = 4.447$, $\log g = 3.7$ and a mass of $14\,M_\odot$ (based on evolutionary models by Maeder & Meynet 1988), as well as a normal (i.e. solar) abundance for B stars in our vicinity. Unfortunately, these authors did not provide error estimates. Finally, the few β Cephei stars with accurate seismic modelling have always ended up outside their observationally determined error box in effective temperature and gravity, to the cooler and less massive part (Thoul et al. 2003 for 16 Lac, Aerts et al. 2003 for HD 129929 and Pamyatnykh et al. 2004 and Ausseloos et al. 2004 for ν Eridani).

The final estimate of the parameters we conservatively adopt for HD 203664, based on all these arguments, is $\log T_{\rm eff} = 4.45 \pm 0.02$ and $\log g = 3.8 \pm 0.2$, while we do not use any constraint at all on its luminosity.

3. Frequency analysis

We searched for frequencies in the Geneva U, B, V filters with the method outlined in Scargle (1982). The results were similar in the B and V filter, so we only provide the detailed analysis for the U and B filter. We accepted frequencies as long as their amplitude is more than 4 times the noise level, which corresponds to a 99.9% confidence level of having found an intrinsic variation rather than a frequency due to noise (Breger et al. 1993, Kuschnig et al. 1997). This criterion is common practise among asteroseismologists these days (e.g. Handler et al. 2003, 2004, 2005). The noise level was computed by averaging the periodogram peaks in the range $[0, 10]\,{\rm c\,d}^{-1}$ after final prewhitening.

The accuracy of the frequencies was calculated as $\sigma_f \sim \sigma/\sqrt{N}AT$ (Horne & Baliunas 1986, Montgomery & O'Donoghue 1999) where the proportionality constant is of order 1 depending on the author (see Cuypers 1987 for a discussion), A is the amplitude of the frequency f, N is the number of data points, T is the total time base and σ is the average error on each individual measurement. We estimated the latter by computing the standard deviation of the noise after final prewhitening, and found it to be 7.1 mmag for the Geneva U filter, 6.5 mmag for B and 7.1 mmag for V.

During a first step, we confirmed the dominant frequency already found by Aerts (2000) from the HIPPARCOS photometry. This frequency appeared clearly in all three considered filters: $f_1 = 6.02885(2)\,{\rm c\,d}^{-1}$ (where the uncertainty of the last digit is given in parenthesis). There was strong aliasing due to the single-site nature of the data (see top panels in Fig. 1) but as the HIPPARCOS data gave us the same value without any daily alias we were sure that we picked the correct frequency for the dominant mode.

After prewhitening, we encountered strong frequency peaks at $n\,{\rm c\,d}^{-1}$. These peaks turned out to due to the slight difference in the average magnitude between the older 0.70m data and the 1.2m Mercator data, which introduces daily aliases of the yearly periods due to the observing seasons. This small difference in average magnitude probably results from the fact that the standard stars used for the Mercator measurements are fainter than those used for the 0.70m Swiss telescope at La Silla. In order not to be disturbed by these daily aliases, we ignored the 49 older measurements in our subsequent frequency analyses.

Prewhitening with f_1 then led to a clear second frequency $f_2 = 6.82902(13)\,{\rm c\,d}^{-1}$ and its aliases in the U filter. This frequency and its aliases fulfilled safely the amplitude requirement (Fig. 1). In the B filter, we found the yearly alias of f_2: $f_2' = 7.83176\,{\rm c\,d}^{-1}$. The HIPPARCOS photometry was of no use to help discriminate among the aliases as of this stage, because there are no significant frequencies in that dataset after prewhitening with f_1. We proceeded by considering f_2 as well as f_2' in a biperiodic fit together with f_1, but this did not help to discriminate between the two options. Therefore, we concluded that either f_2 or f_2' is the true second frequency. Phase plots for f_1 and f_2 for the three Geneva UBV filters are provided in Fig. 2. The curves in the lower panel are indistinguishable in quality from those for f_2'.

After subsequent prewhitening with either f_2 or f_2' we continued the search for new frequencies. In this way, we found $f_3 = 4.81543(14)\,{\rm c\,d}^{-1}$ or one of its aliases. This frequency fulfilled the amplitude requirement in B, but not in V and only barely in U. It must therefore be regarded as a candidate frequency only without further observational confirmation. Moreover, we could not distinguish the frequency from its aliases from multiperiodic fits to the lightcurves. Unlike for the

[1] available only in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5)

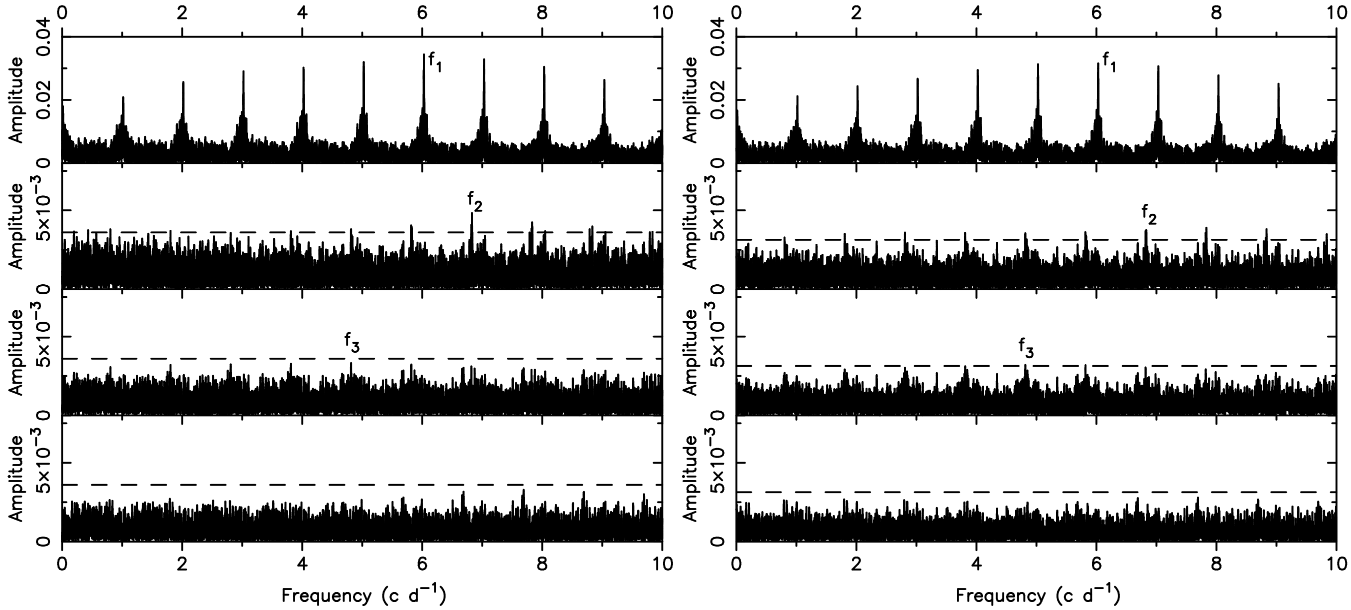

Fig. 1. The periodograms for the Geneva U (left) and B (right) data of HD 203664 after subsequent stages of prewhitening with the frequencies provided in the text. The amplitudes are expressed in magnitudes. The dashed horizontal line indicates the 4σ level determined in the way explained in the text.

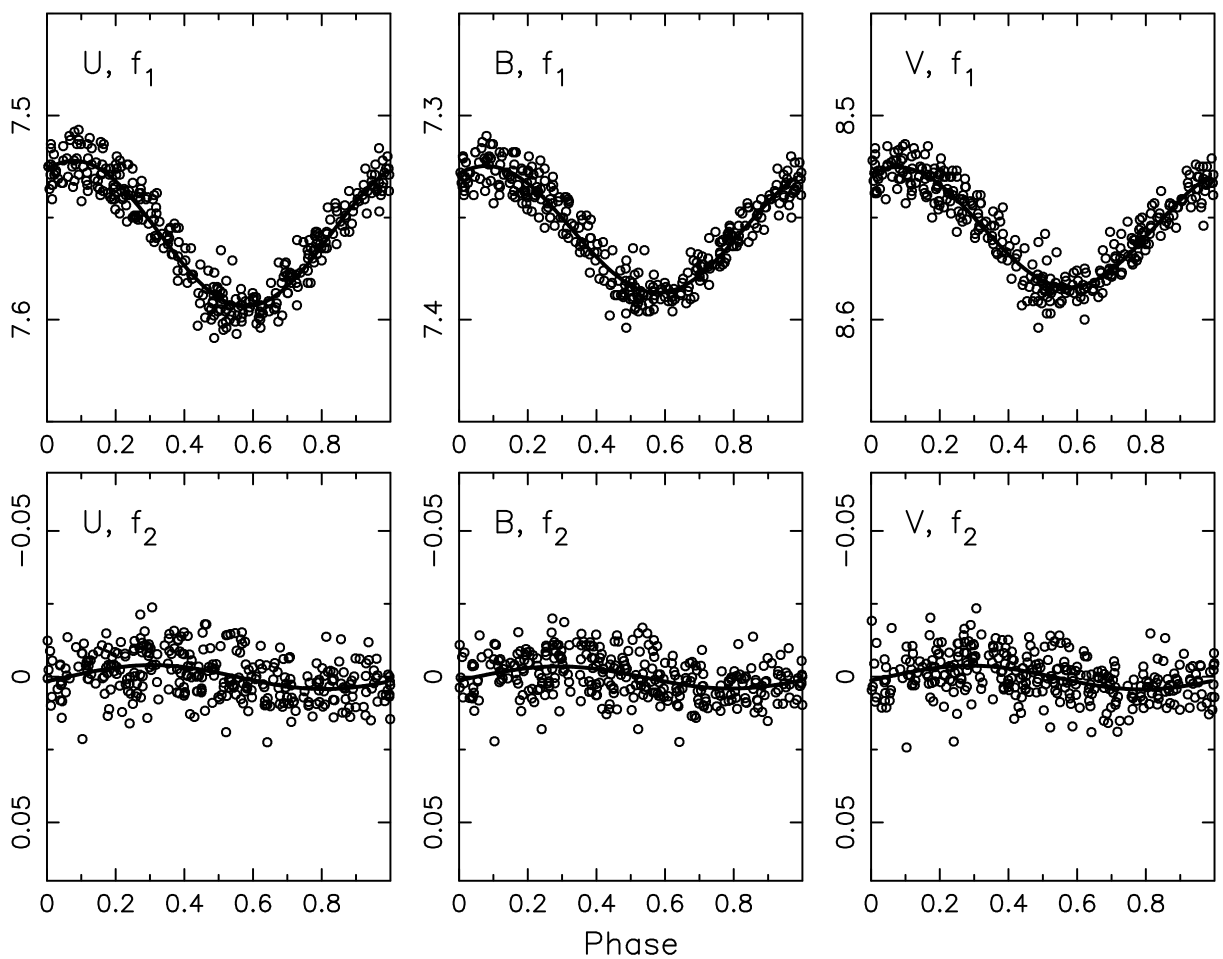

Fig. 2. Phase diagrams of the U (left), B (central), V (right) lightcurves of HD 203664 for f_1 (upper) and for f_2 after prewhitening with f_1 (lower). The dots are the data and the full line is a sinusoidal fit with fixed indicated frequency. Note the different scale of the y-axes of the upper versus lower plots.

second frequency, numerous aliases of f_3 gave equally good fits.

The best overall fits to the U, B, V data was achieved by taking the values for $f_1, \ldots, f_3$ as listed above, but we cannot exclude to have missed a true frequency and have taken an alias for any of f_2, f_3. We will not use the latter frequency to make seismic inferences further on and in the case of the second frequency we consider each time both f_2 and f_2'.

Any other frequencies found after prewhitening do no longer reach four times the noise level (see bottom panels of Fig. 1) so we stop the frequency analysis at this point.

A firm conclusion is that HD 203664 is a multiperiodic β Cephei star with one dominant mode having an amplitude about ten times larger than the ones of its other modes. The three frequencies f_1, f_2, f_3 reach an amplitude of respectively 38.8, 4.5, 4.0 times the noise level in U, of 38.4, 4.7, 4.2 times the noise level in B and of 31.8, 4.5, 3.2 times the noise level in V.

4. Amplitude ratios and mode identification

Table 1 lists the results for the amplitudes and phases of least-squares fits with f_1, f_2, f_3 fixed at their values mentioned above. The overall variance reduction is also listed. Using f_2' rather than f_2, or any alias of f_3 rather than these frequencies, led to amplitude and phase values within the error bars listed in Table 1. As a comparison, we mention that a monoperiodic fit with f_1 has a variance reduction which is typically 5 to 8% lower depending on the filter. The amplitudes were each time largest in the U filter, as is expected for the oscillation modes in the β Cephei stars.

We observed that the phases are equal to within their accuracy for the three modes in the seven filters. Hence, we made use only of amplitude ratios as a mode identification diagnostic. This is according to the common procedure for the β Cephei stars.

In order to attempt mode identification, we proceeded as follows. We computed stellar models using the Code Liégeois d'Évolution Stellaire (CLES) kindly provided by R. Scuflaire. For the details on the input physics, used opacity tables and equation of state, we refer to Ausseloos et al. (2004). We restricted to models with $X = 0.70$, $Z = 0.02$, in agreement with the abundances derived by Little et al. (1994), and without core convective overshooting. For each value of the mass, we computed evolutionary tracks from the ZAMS until the TAMS and we selected those that are within the observed range of $T_{\rm eff}$ and $\log g$ derived in Sect. 2. In doing so we considered a range in mass from 12 to 16 $M_\odot$ in steps of 0.5$M_\odot$. Subsequently, we computed eigenfrequencies and eigenfunctions for each of the models using the non-adiabatic oscillation code MAD (Dupret 2001) kindly made available by M.-A. Dupret. For each of the models, we selected the eigenfrequency which was closest to the measured $f_i, i = 1, \ldots, 3$ and considered its theoretical non-adiabatic amplitude ratios following the formalism by Dupret et al. (2003). Finally, we compared all these theoretically predicted amplitude ratios with the observed ones for each of the detected frequencies. In this way, we performed a mode identification which is independent of one particular stellar model, but that considers a large range of theoretical models covering safely the current mass estimate of HD 203664.

The result of this procedure for the dominant mode can be found in Fig. 3 for $\ell = 0, \ldots, 4$. Thanks to the small error bars of the observed ratios, we readily identified this mode as a dipole mode. Indeed, the $\ell = 2$ solution was the only one compatible with the high-quality data. The strongest mode of HD 203664 is therefore clearly non-radial. A similar situation occurs in several other β Cephei stars (see, e.g., Heynderickx et al. 1994).

The other two modes had too high errors on their amplitude ratios to be able to discriminate among the ℓ-values. We illustrate this for the mode with frequency f_2 in Fig. 4. While the agreement between the theoretical predictions and the observations is best for $\ell = 2$, we cannot firmly exclude the other ℓ-values of the non-radial modes. We do find that the mode with frequency f_2 is unlikely to be radial. The same result is obtained if we take f_2' rather than f_2.

The ratios for the modes with f_3 are even more uncertain and do not provide any constraint at all so the corresponding mode identification plot is omitted here.

In an attempt to confront these seismic observational constraints with standard models, we used the ones mentioned above, i.e. with masses ranging from 12 to 16 $M_\odot$, $X = 0.70, Z = 0.02$ and without core overshooting ($\alpha_{\rm ov} = 0.0$). We computed all their oscillation frequencies for zonal modes of $\ell = 0, \ldots, 3$ without taking into account the effects of rotation. We point out that this is a simplification of the true situation, because second-order rotational effects imply frequency shifts, even for zonal modes. Moreover, mode coupling occurs due to rotation for modes whose degree differs by 2 if their frequencies are close together (e.g. Soufi et al. 1998, Daszyñska-Daszkiewicz et al. 2003). However, we postpone a sophisticated interpretation of HD 203664's observed frequencies for the time being and restrict to a confrontation with standard models here.

Typically three or four radial orders of an $\ell = 2$ zonal mode fitting the frequency f_1 resulted from the standard models from the ZAMS to the TAMS, for each of the considered masses between 12 and 16 $M_\odot$. Forcing a simultaneous fit to an $\ell = 2$ zonal mode for f_2 was achieved for several of the models that already fit f_1. An examples of the mode spectrum of evolutionary models with $M = 13\,M_\odot$ is provided in Fig. 5, in which all the $\ell = 0, \ldots, 3$ mode frequencies are compared with f_1 and f_2. The vertical dashed-dot line indicates the lower limit of the observed effective temperature interval, i.e. HD 203664 must occur to the left or close to this line, pointing out its young age already found by Aerts (2000). The model indicated by the full vertical line provides a good fit to f_1 and f_2 for zonal $\ell = 2$ modes. This model has parameters $X = 0.70$, $Z = 0.02$, $M = 13\,M_\odot$, $\log\,T_{\rm eff}$=4.429, $\log g = 3.98$, $\log L/L_\odot$=4.24, $R = 6.12\,R_\odot$, a central hydrogen abundance $X_c = 0.438$, an age of 7.5×10^6yr and no core overshooting. These $T_{\rm eff}$ and $\log g$ values are compatible with the estimates from observations provided in Sect. 2. Moreover, non-adiabatic computations with MAD indicate that the two modes are excited for this model.

Table 1. Results of harmonic fits to the Geneva lightcurves of HD 203664. A stands for the amplitude, expressed in millimag, and ϕ for the phase, expressed in 2π radians. The adopted reference epoch for $\phi = 0.0$ corresponds to HJD 2450000.0.

		U	B_1	B	B_2	V_1	V	G
f_1	A	36.3±0.7	32.5±0.8	31.7±0.7	31.4±0.7	30.0±0.8	30.0±0.7	29.1±0.8
	ϕ	0.077±0.001	0.078±0.001	0.078±0.001	0.077±0.001	0.079±0.001	0.075±0.001	0.077±0.002
f_2	A	4.2±0.7	3.9±0.6	3.9±0.6	4.0±0.7	3.7±0.7	4.2±0.6	3.6±0.6
	ϕ	-0.210±0.026	-0.226±0.027	-0.226±0.024	-0.199±0.028	-0.209±0.031	-0.225±0.023	-0.240±0.029
f_3	A	3.7±0.8	3.6±0.8	3.5±0.7	3.5±0.7	2.7±0.7	3.0±0.7	1.8±0.7
	ϕ	0.172±0.010	0.165±0.009	0.166±0.009	0.189±0.014	0.205±0.024	0.189±0.016	0.238±0.051
variance reduction		93.2%	91.2%	92.5%	91.3%	89.3%	91.1%	87.7%

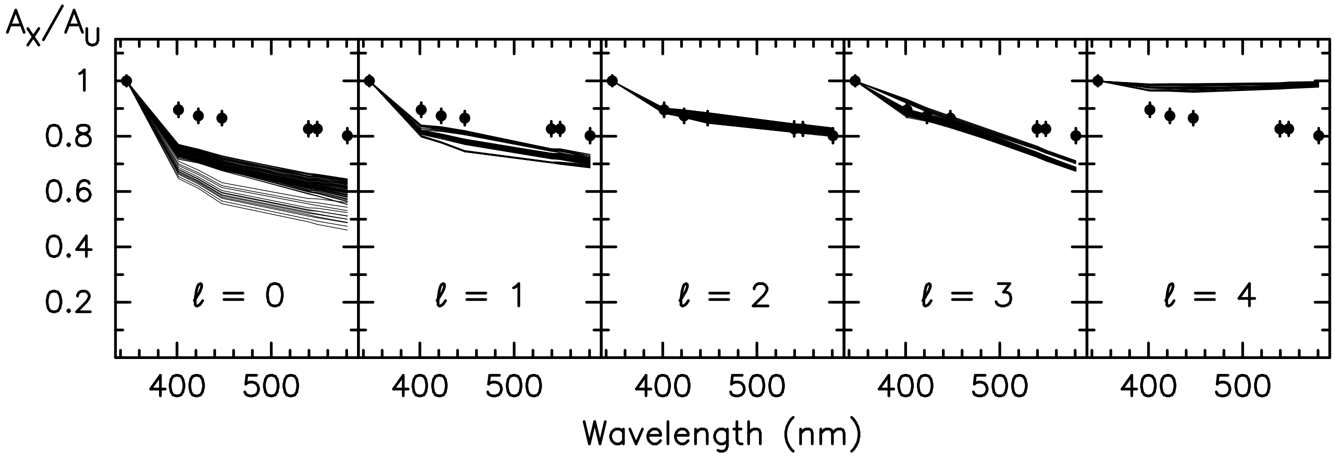

Fig. 3. Observed amplitude ratios A_X/A_U (filled circles) and their uncertainties for the dominant mode with frequency f_1 of HD 203664, where A_X stands for any of the amplitudes in the seven Geneva filters U, B_1, B, B_2, V_1, V, G. The lines represent theoretical predictions in the non-adiabatic treatment of the oscillations for stellar models within the mass range $[12, 16]\,M_\odot$ during the main-sequence phase and fulfilling the error box in $T_{\rm eff}$ and $\log g$ derived in Sect. 2.

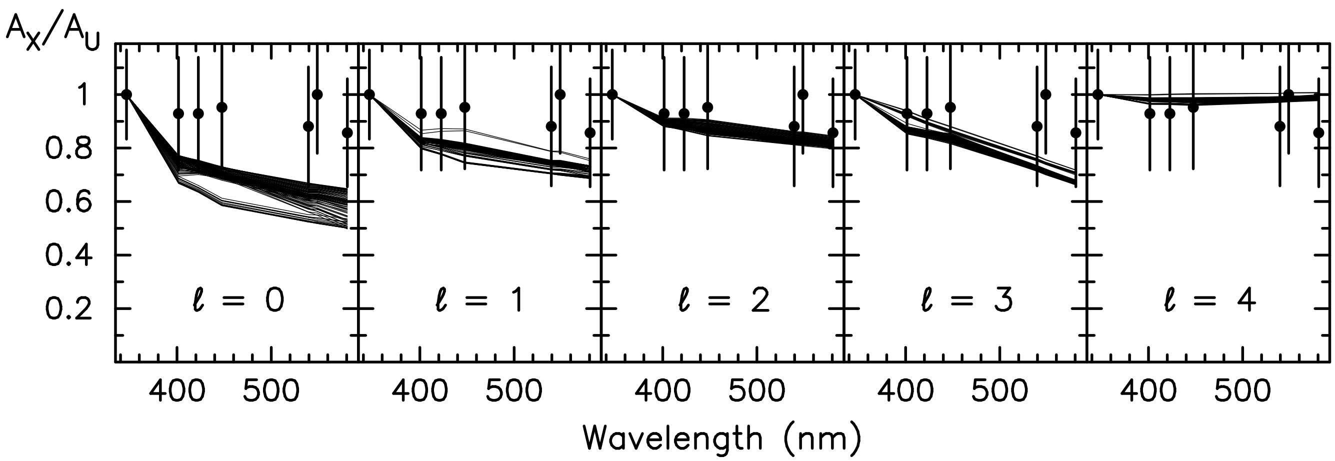

Fig. 4. Same as Fig. 3, but for the mode with frequency f_2.

Fitting f_1 and f_2' as two zonal $\ell = 2$ modes is also possible if their radial order differs by 2, but the models for which such a fit is obtained are somewhat more evolved which is less likely due to the observational constraint on the effective temperature. Moreover, the frequency fit is not as good as for f_2. Any of the models with $M \neq 13\,M_\odot$ while keeping X, Z, $\alpha_{\rm ov}$ fixed do not provide an equally good fit to both f_1 and f_2 (or f_2') as the model indicated by the vertical line in Fig. 5.

We thus find that a good fit for f_1 and f_2 as $\ell = 2$ modes can only be achieved close to an avoided crossing *if we restrict to zonal modes.* Modes near avoided crossings have very good potential to probe the interior of a star. However, we have no

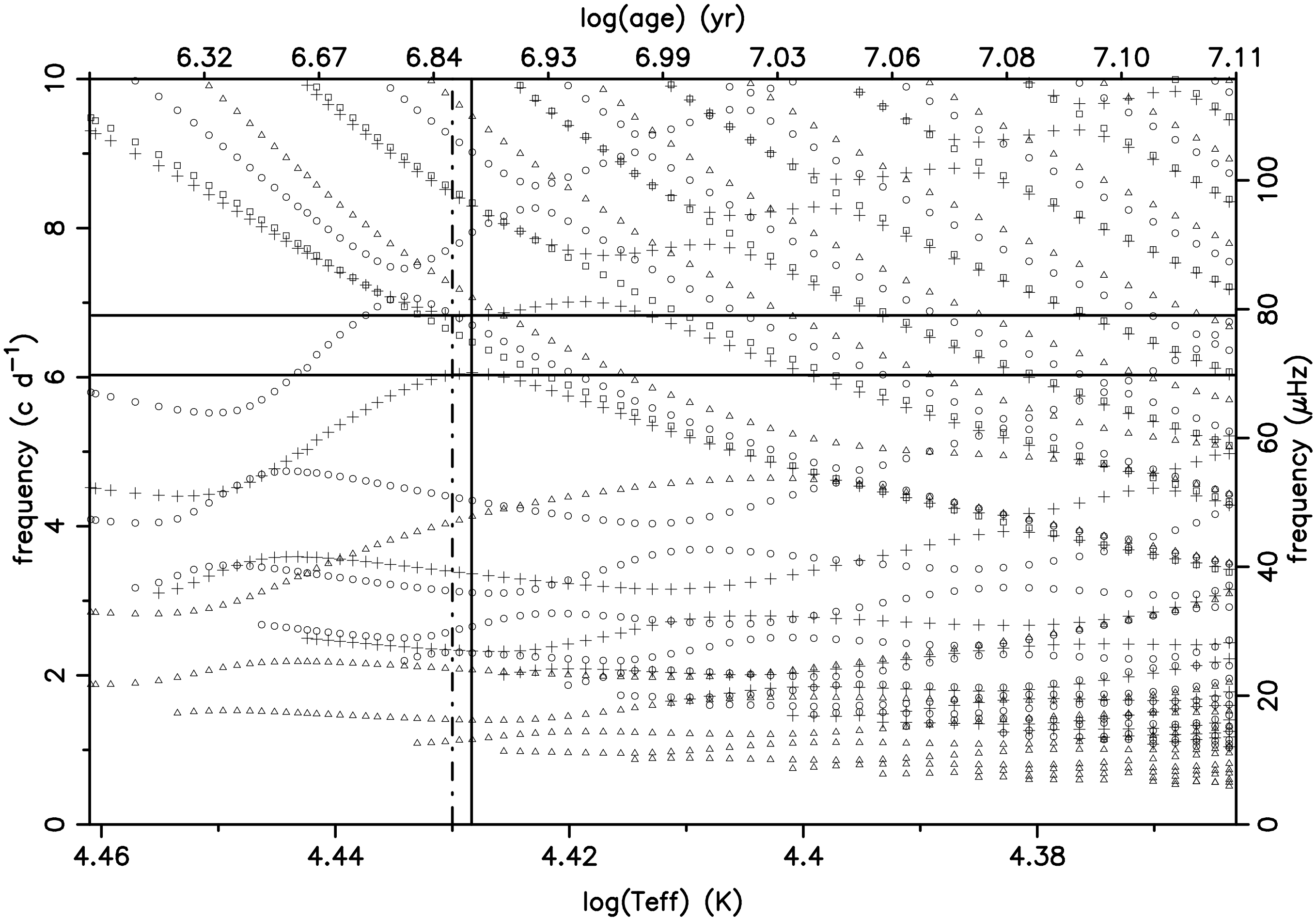

Fig. 5. Theoretical frequency spectra for stellar models with $M = 13\,M_\odot$, $X = 0.70$, $Z = 0.02$ without core overshooting from the ZAMS until the TAMS. The star's position is to the left of the vertical dashed-dot line according to the $T_{\rm eff}$-range derived in Sect. 2. The symbol convention for the modes is as follows: squares for $\ell = 0$, triangles for $\ell = 1$, plus sign for $\ell = 2$, circles for $\ell = 3$. Higher $\ell-$values are not shown for clarity. The observed frequency values f_1 ($\ell = 2$) and f_2 (likely $\ell = 2$) are indicated by the horizontal lines. The vertical line indicates the model for which an exact match to f_1 and f_2 is obtained for two zonal $\ell = 2$ modes.

conclusive observational evidence to restrict to $m = 0$ and so other evolutionary models may also lead to an equally good fit of the two considered frequencies for non-zonal modes.

At present we have too restrictive observational constraints to perform a precise fitting procedure (e.g. as outlined in Ausseloos et al. 2004), i.e. to scan in detail the parameter space of any possible stellar model as a function of $(X,\ Z,\ \alpha_{\rm ov},\ M)$. Indeed, besides the fact that we cannot exclude a different $\ell-$value for the mode with frequency f_2 (or f_2'), we have no information on the azimuthal number of the modes nor do we know the surface rotation frequency of the star. Assuming that f_1 and f_2 represent to a good approximation the central peaks of frequency multiplets is too restrictive because the rotational frequency must be of order 0.5 c d^{-1} or larger given that vsini=200 km s^{-1}.

We can only conclude that the currently observed oscillation spectrum of HD 203664 can easily be explained by standard stellar models and excitation computations and that we have insufficient information to further constrain the stellar parameters from asteroseismology at present.

5. Discussion

We have shown the large-amplitude β Cephei star HD 203664 to be a multiperiodic non-radial oscillator from single-site long-term multicolour Geneva photometry. The dominant mode was unambiguously identified as a dipole $\ell = 2$ mode from its amplitude ratios. The frequencies of the star are compatible with standard stellar models of massive stars during the main sequence phase.

There are at present nine other β Cephei stars known to have a peak-to-peak V amplitude larger than the one of HD 203664 (Stankov & Handler 2005). Only one of these ten stars is monoperiodic (BW Vul) since multiperiodicity was recently discovered in HD 180642 (Aerts et al., in preparation). Three of them have a confirmed dominant radial mode (ν Eri – Handler et al. 2004, BW Vul – Aerts et al. 1995, HD 180642 – unpublished), three have an $\ell = 1$ mode (IL Vel – Handler et al. 2003, 12 Lac – Handler et al. 2005, KP Per – Saesen et al., in preparation) and two have an $\ell = 2$ mode (KZ Mus – Handler et al. 2003, HD 203664 – this paper). We do not find any obvi-

ous relation between these results and the projected rotation velocity of the stars (Stankov & Handler 2005). HD 203664 is by far the most rapid rotator among them, with vsini=200 $\mathrm{km\,s^{-1}}$ which is more than twice as high as for any of the other large-amplitude β Cephei stars. From the mass and $\log g$ estimates given in Sect. 2, we find a critical velocity of 480 $\mathrm{km\,s^{-1}}$ and hence vsini / $v_{\rm crit}$ = 42%.

The stellar parameters and internal structure of HD 203664 can only be constrained further by means of elimination of the alias problems presented here for the low-amplitude modes (i.e. from a multisite campaign as those performed by Handler et al. 2003, 2004, 2005), by subsequent unambiguous identification of their degree from amplitude ratios and by further identification of their azimuthal number through high-resolution spectroscopy. Given its visual magnitude of 8.6, its oscillation periods near 4 hours and its low-amplitude modes, together with the data requirements for such type of spectroscopic analysis (e.g. Aerts & Eyer 2000), one needs, besides a photometric multisite campaign, at least one week of 8-m class telescope time to achieve mode identification and subsequent interpretation of the oscillations of this massive hot rapid rotator among the β Cephei stars.

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